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The relation between specific humidity deficits at screen level and those in crop canopies

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1. Introduction

Potential transpiration is calculated usually with simplified versions of the combination formula; the latter is written exactly as

$$\lambda E = \frac{\Delta'(R_N - G) + \varrho c_p \delta q / r_a}{\Delta' + c_p(1 + r_s/r_a)/\lambda} \qquad (1)$$

where $\Delta' = \partial q_w / \partial T$

q_w = saturation specific humidity

δq = specific humidity deficit at reference level (screen height of 1.2 m usually).

r_a = resistance to transfer of heat and water vapour from their mean source height in the canopy to height at which δq is measured.

The formula is not applied usually in its exact form, to avoid the tedious calculation of r_a, and because of uncertainties in selecting a value for r_s. Minimum values for r_s are around 20 sm^{-1} (if r_a is calculated on the assumption that $z_T = z_q \simeq 0.2 z_o$) but increase, inter alia, as a result of progressive stomatal closure caused by increasing specific humidity deficit. This Memorandum explores the daytime relationship between δq at screen height and the average humidity deficit within the crop canopy (which is that affecting stomatal closure) for a range of values of meteorological variables. The results are intended to be used in the production of a simplified version of Eq (1) intended for reasonably precise estimation of potential transpiration; this revised equation is under development at present.

2. Theory

In unstable density stratification the variations with height of specific humidity and potential temperature over a rough surface are approximated by the expressions

$$\frac{q(z) - q(0)}{q_*} = \frac{\theta(z) - \theta(0)}{T_*} = \frac{1}{k}\left[\left(\ln\left((1-y_1)/(1+y_1)\right)\right)\right]_{z_T,q}^{z-d} \qquad (2)$$

where $q_* = -E/\rho u_*$

$T_* = -H/\rho c_p u_*$

$z_{T,q} = 0.2 z_o \simeq 0.02h$ where h is height of canopy

d = displacement height $\simeq 0.63h$ (Monteith 1973)

L = Monin-Oboukhov length $= -u_*^3 (T+273)\rho c_p / kg(H + 0.07\lambda E)$

$k = 0.4$

$y_1 = (1 - 16(z-d)/L)^{1/2}$

(Paulson 1970). The wind profile, from which u_* may be determined, is

$$u(z) = \frac{u_*}{k}\left(\ln\left(\frac{z-d}{z_o}\right) - \psi_M\left(\frac{z-d}{L}\right)\right) \qquad (4)$$

where $$\psi_M\left(\frac{z-d}{L}\right) = 2\ln\left(\frac{1+y}{2}\right) + \ln\left(\frac{1+y^2}{2}\right) - 2\tan^{-1} y + \pi/2 \qquad (5)$$

with $$y = (1 - 16(z-d)/L)^{1/4} \qquad (6)$$

With stable density stratification (which will occur in daytime conditions with low or moderate available energy but high evaporative demand) the appropriate relations are

$$u(z) = \frac{u_*}{k}\left(\ln\left(\frac{z-d}{z_o}\right) + 5.2(z-d-z_o)/L\right) \qquad (7)$$

$$\frac{q(z) - q(o)}{q_*} = \frac{\theta(z) - \theta(o)}{T_*} = \frac{1}{k}\left(\ln\left(\frac{z-d}{z_o}\right) + 5.2(z-d-z_{T,q})/L\right) \qquad (8)$$

(Webb 1970)

The necessary calculations were performed after specifying suitable ranges of available energy (50-500 Wm^{-2}), 10 m wind speeds (2-10 ms^{-1}), screen specific humidity deficits and temperatures (0.001 - 0.010, 5-25 deg C), and bulk stomatal resistances. These last were assumed to vary from 20 sm^{-1} (a freely transpiring dense canopy) to 60 sm^{-1} (representing either significant stomatal closure due to large specific humidity deficit, or incomplete crop cover - it was assumed that the soil was at field capacity but with a dry surface).

The equations cannot be solved directly because L is not evaluable until the available energy is partitioned between H and λE. The simplified procedure adopted used the following steps:

(i) For each specification of the variables, approximate values for H and λE were deduced from Eq (1) assuming near-neutral conditions. The wind speed at screen height was estimated first from Eq (4), putting $\psi_M = 0$ and r_a was then deduced from

$$r_a = \frac{1}{k^2 u(1.2)} \cdot \ln(z/z_o) \cdot \ln(z/z_{T,q}) \qquad (9)$$

: the calculations were performed for z_o values of 0.01 and 0.03 m, appropriate to medium-length, and long grass, and 0.1 m (representing fully-

grown wheat or barley).

(ii) L was calculated.

(iii) Improved values for L and u_* were obtained by iteration, using Eq (4) or (7) as appropriate.

(iv) A more-exact value for r_a was deduced from

$$r_a = \frac{1}{k u_*} \left[\ln \left((1-y_{1})/(1+y_{1}) \right) \right]_{z_{T,q}}^{z-d} \qquad (10)$$

(v) The program was re-entered at the latter part of step (i) and new values for H and λE calculated with the r_a values from step (iv). Revised value for r_a were then deduced by steps (ii) to (iv). Repetition of this iteration produced final values for H and λE .

(vi) Average canopy values of specific humidity and temperature (assumed to be given by $q(o)$ and $T(o)$) were deduced using the relations.

$$q(1.2) - q(o) = -E.r_a/\rho \qquad (11)$$

$$T(1.2) - T(o) = -H.r_a/\rho c_p - 0.01(1.2-(d+z_{T,q})) \qquad (12)$$

(vii) The specific humidity deficit within the canopy was calculated from the results of (vi) and the specified screen values of T and δq

3. Results and discussion

It is convenient to summarise the results in graphical rather than tabular form. A selection are plotted in Figure 1. Some of the plots include values of r_s and T which are mutually exclusive since it is unlikely that stomata will be fully open at temperatures as low as 5 deg C; values given for this temperature may be used to estimate deficits at higher temperatures by interpolation in conjunction with the plots for 25 deg C.

It is clear from Figure 1 that there is no simple relation between screen and canopy humidity deficits. The more easily explicable results are summarised briefly as follows:

Effect seen	Cause
a. P ($= \frac{\delta q(\text{canopy})}{\delta q(\text{screen})}$) increases with increasing r_s	High r_s reduces evaporation, increases canopy temperature, hence increases δq in canopy.
b. increases with increasing available energy.	The Bowen ratio increases as $R_N - G$ increases because the aerodynamic contribution to evaporation is nearly independant of $R_N - G$. In higher wind speeds and with large δq (screen) the Bowen ratio may be negative (evaporative demand $> R_N - G$). The increase of Bowen ratio with increasing $R_N - G$ is the result of relatively warmer foliage with correspondingly larger canopy deficits.

Effect seen	Cause
c. P is greater than 1 for moderate or high $R_N - G$ and small δq (screen) but less than 1 for all available energies at high (screen).	Small δq (screen): aerodynamic evaporative demand is relatively low, and hence foliage temperature relatively high. Large δq (screen): aerodynamic evaporative demand is larger, Bowen ratio smaller, foliage cooler.

Other variations of P such as those caused by variations of wind speed or surface roughness cannot be explained simply, because of the complexity of the interacting processes causing them.

The results may be displayed in a slightly different and sometimes more convenient way by converting the humidity deficits to relative humidities. It is often of interest to know the relation between screen and canopy relative humidities when screen values are high (say 90%): a summary of these results is given in Table 1. Perhpas of most interest are the data for low available energy because it is unlikely that RH's as high as 90% persist for long when available energies are 200 or more Wm^{-2}. It is seen that at this low energy (50 Wm^{-2}) the canopy RH's are 95% or greater even for wind

Table 1 Relative humidities in canopy when relative humidity in screen is 90% at T = 15 deg C

z_o (m)	$R_N - G$ (Wm^{-2})	u(10) (ms^{-1})	RH (canopy) (%)
0.01	50	2	97
		10	96
	200	2	92
		10	92
	500	2	81
		10	82
0.1	50	2	97
		10	95
	200	2	92
		10	91
	500	2	82
		10	84

as high as 10 ms^{-1}.

A weakness in the approach followed in this memorandum is the assumption that conditions throughout the canopy can be represented adequately by those calculated for a single height close to the zero-plane displacement. It is partly reassuring in this context to record the comments of Penman and Long (1960), who noted that measurements in a fairly sparse wheat crop (leaf area index $\simeq$ 2) about 0.7 m high showed humidity deficits varying usually by

less than ±10% through the crop. Such a sparse crop is easily ventilated and denser stands where more of the incoming radiation is absorbed in the upper part of the canopy and into which wind can penetrate less easily may show larger variations of humidity deficit: certainly this will be the case after wetting by rain where evaporation deep in the stand may proceed rather slowly.

Penman and Long give some data obtained at Rothamsted midday on 5 June 1955 which may be compared with the present results. In a dense stand of wheat 30 cm high the specific humidity deficits at 12.5 and 25 cm were .0036 and .0048 (mean .0042) compared with .0051 at a height of 2 m above ground. The ratio of deficits is therefore 0.82 (± 0.12). The day was sunny ($R_n - G \sim 400\ Wm^{-2}$) with wind speed of 4 ms^{-1} at 10 m and temperature around 20 deg C. z_o was around 0.03 m and entering Figure 1 with these values produces an estimated value for P of 0.5-0.6. The agreement is actually slightly poorer than these figures indicate because P is referred to a screen height rather than 2 m, though the gradient of P between these two heights would be small in this situation. On 4th June 1955, during mid to late afternoon observations on the same crop gave a ratio of 0.49 when $R_n - G \sim 250\ Wm^{-2}$, $u \simeq 4\ ms^{-1}$, δq (2 m) $\simeq$ 0.005 and $T \simeq$ 16 deg C. In this case P from Figure 1 is 0.3-0.4. Thus there appears to be a systematic difference between the results of the present treatment and some actual field data covering a rather restricted range of conditions. The point should be made however that the crop while fairly dense was also short and immature and hence despite rain which fell early on the 4th the crop resistance r_s was probably larger than 20 sm^{-1}, due to less than maximum leaf area. If r_s had been say 30-40 sm^{-1} then agreement between the field data and the present treatment would have been reasonably satisfactory.

Any comments or suggestions on this paper should be referred to the author.

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References

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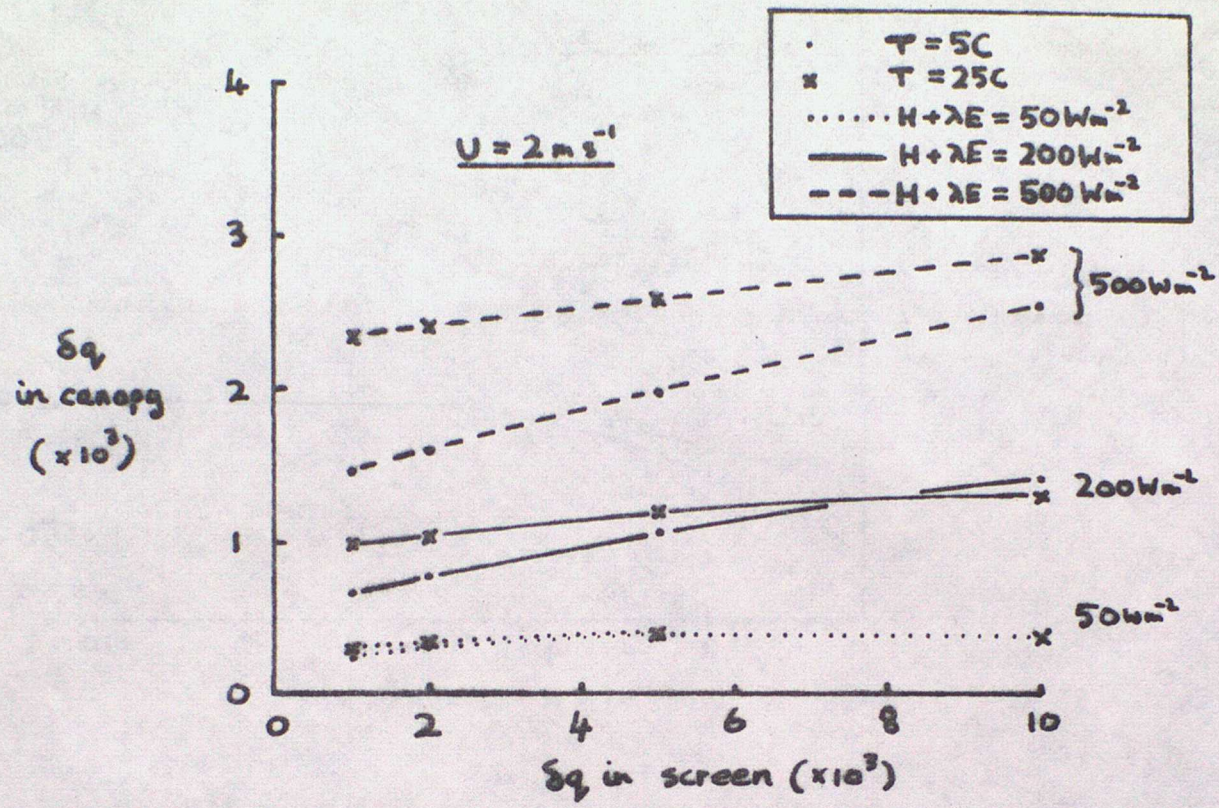
Paulson, C.A. 1970 The mathematical representation of wind speed and temperature profiles in the unstable atmospheric surface layer, J. Appl. Met., 9, 857-861.

Penman, H.L. and Long, I.F. 1960 Weather in wheat: an essay in micrometeorology, Q.J.R.Met. S., 86, 16-50.

Webb, E.K. 1970 Profile relationships: the log-linear low and extension to strong stability, Q.J.R.Met. S., 96, 67-90.

(a) $z_o = 0.01\,m$; $r_s = 20\ sm^{-1}$



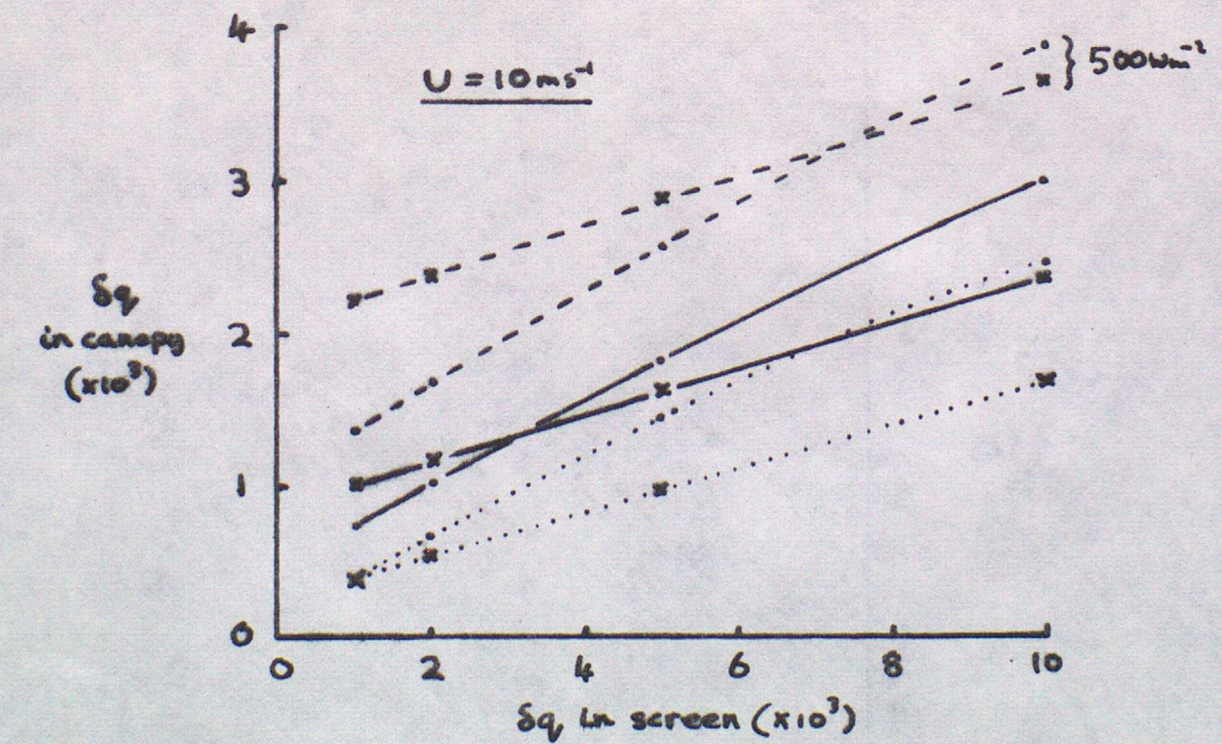
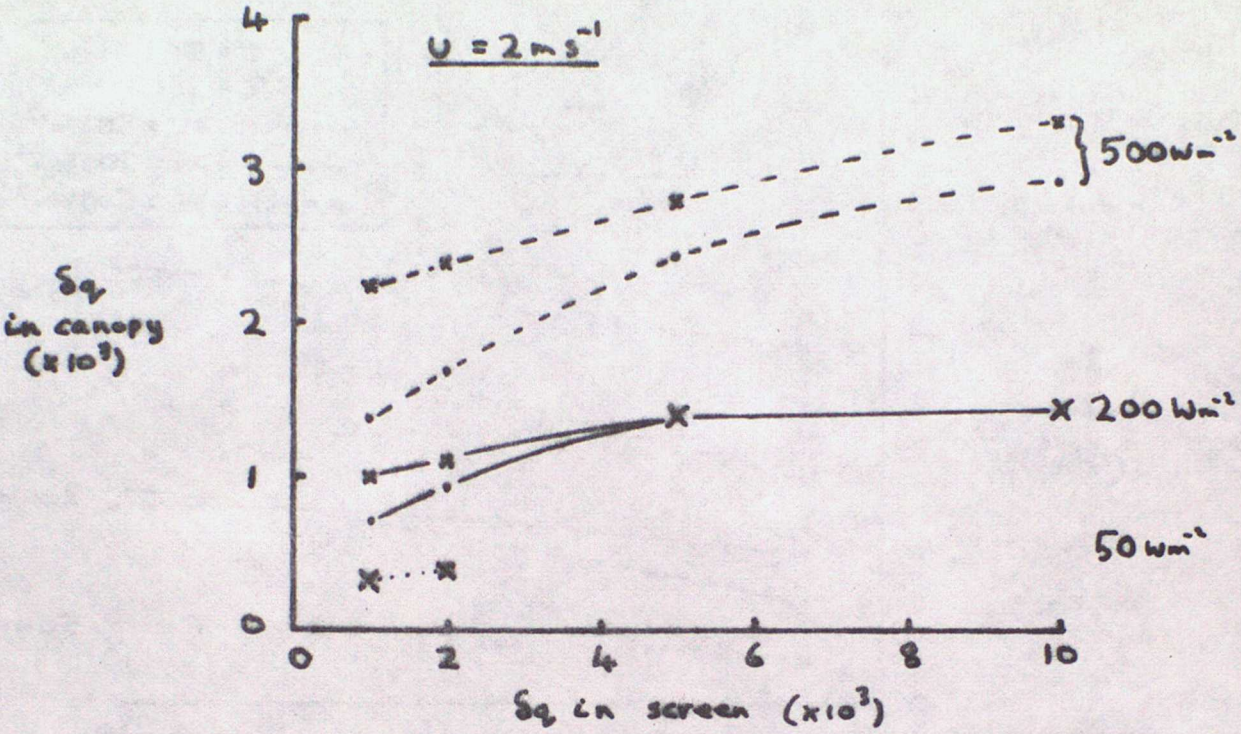


Figure 1 Comparison of specific humidity deficits in screen and canopy

(b) $z_o = 0.1m$; $r_s = 20 sm^{-1}$



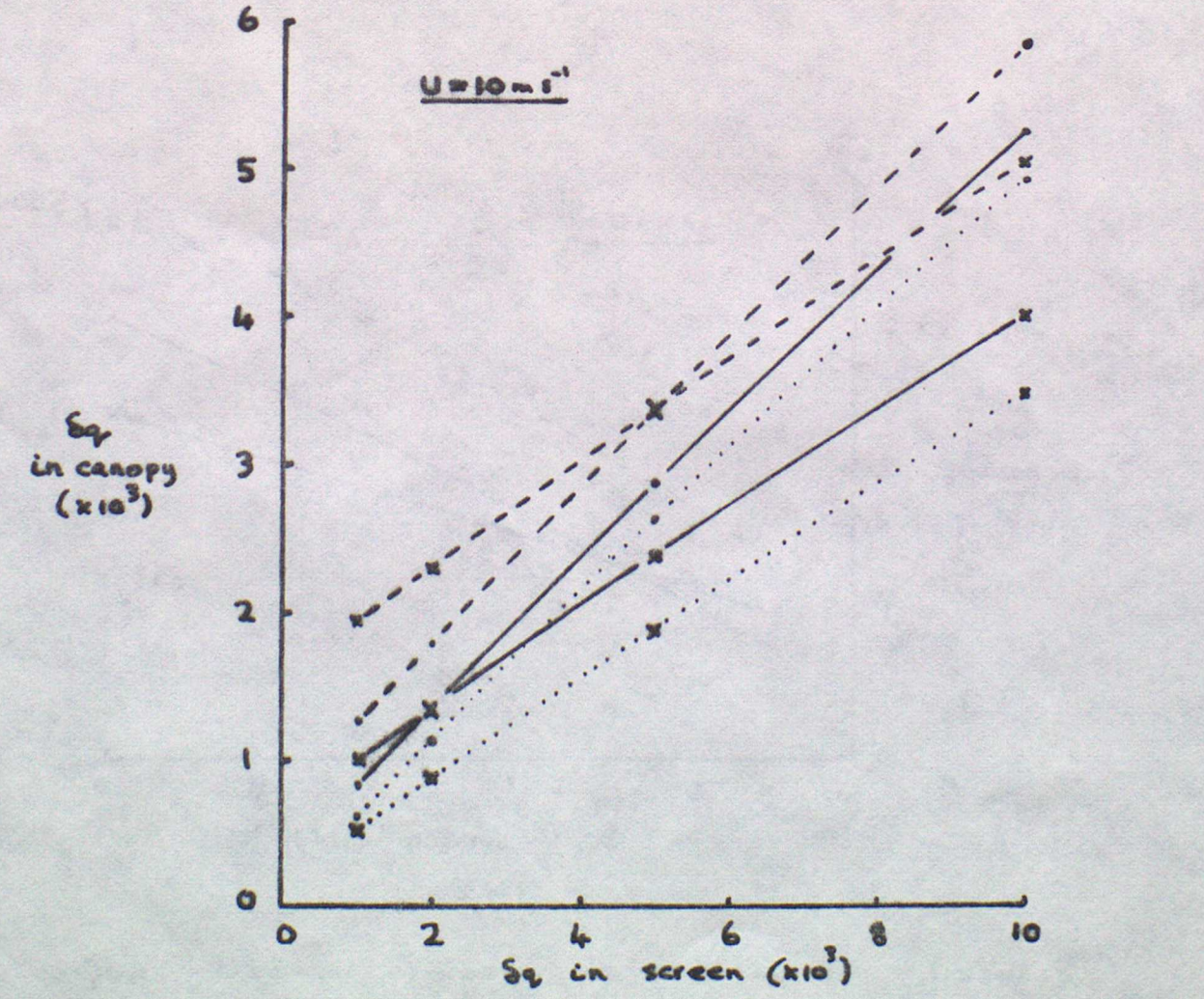
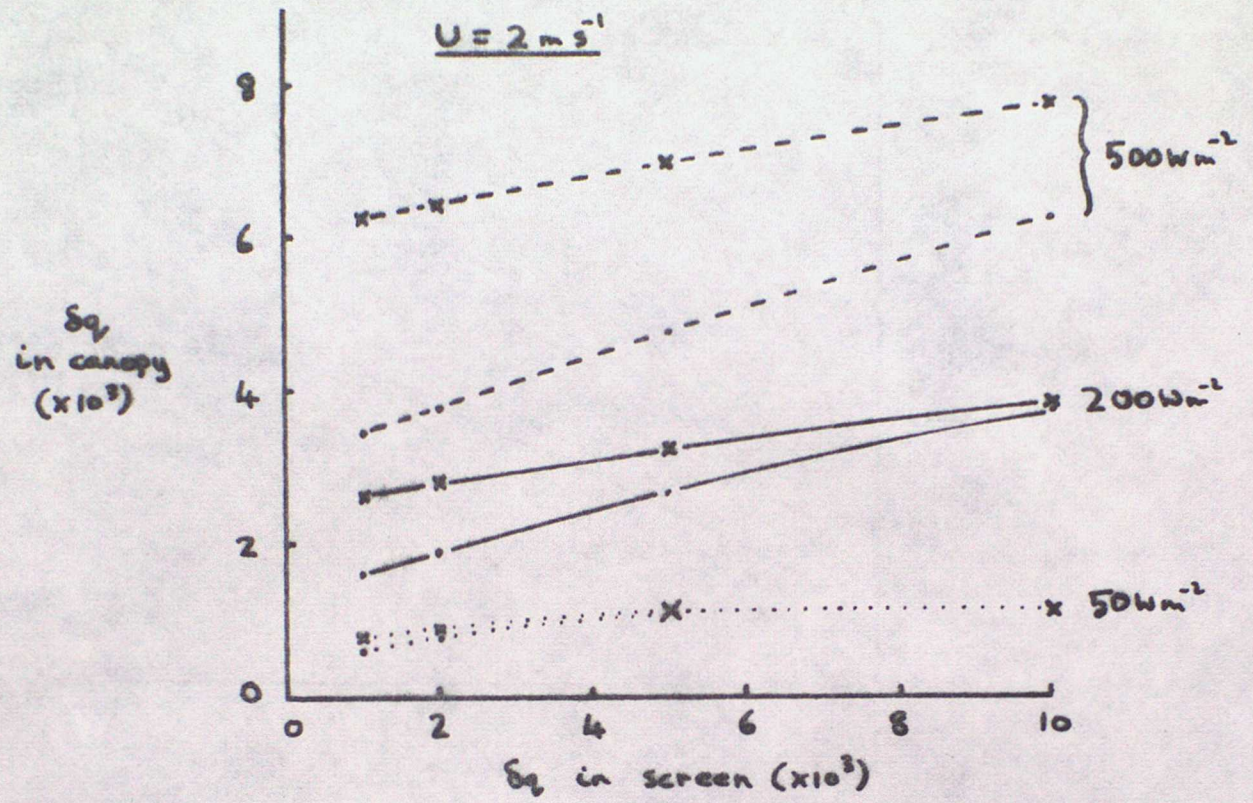


Figure 1 (Continued)

(c) $z_o = 0{\cdot}01\,m$; $r_s = 60\,sm^{-1}$



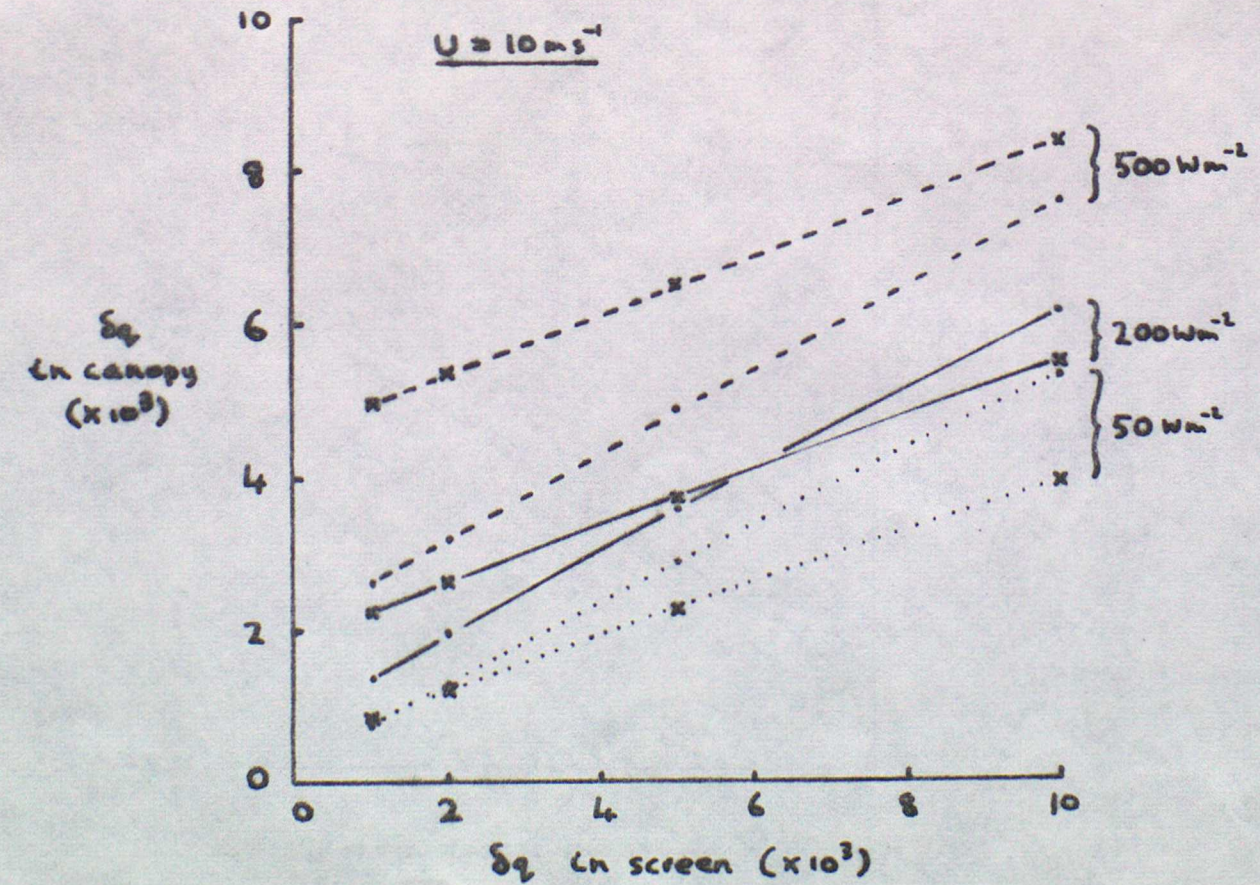
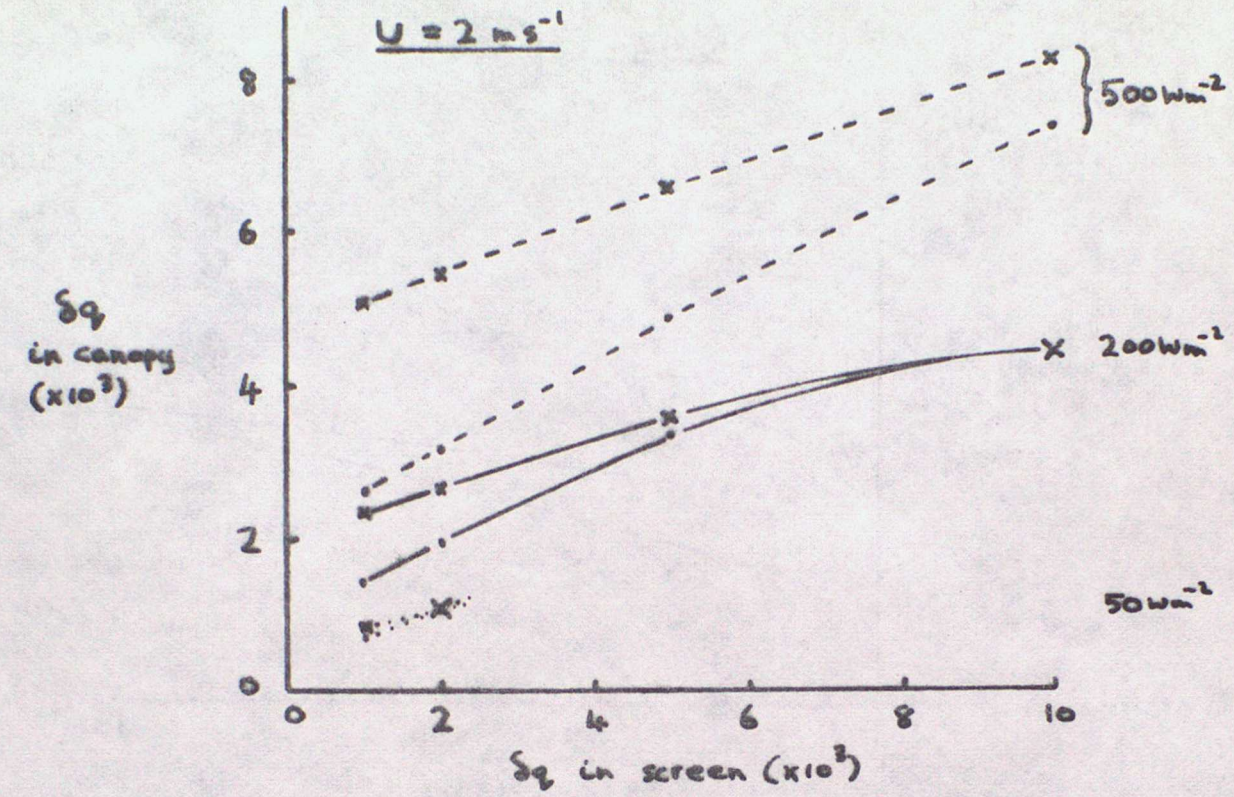


Figure 1 (Continued)

(d) $z_o = 0.1m$; $r_s = 60\ sm^{-1}$



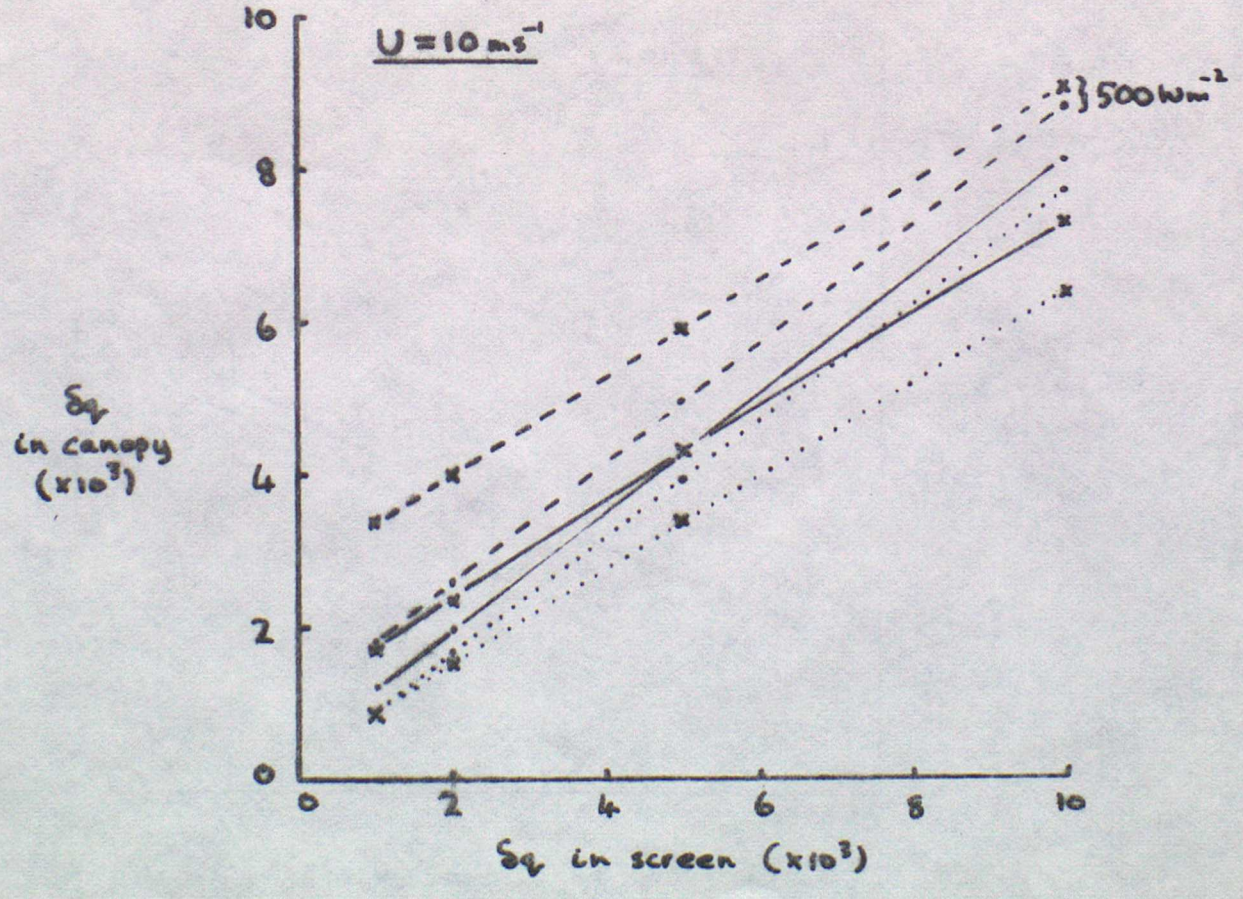


Figure 1 (Continued)